

# ELLIPTIC CURVES OF UNBOUNDED RANK AND CHEBYSHEV'S BIAS

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**ABSTRACT.** We establish a conditional equivalence between quantitative unboundedness of the analytic rank of elliptic curves over  $\mathbb{Q}$  and the existence of highly biased elliptic curve prime number races. We show that conditionally on a Riemann Hypothesis and on a hypothesis on the multiplicity of the zeros of  $L(E, s)$ , large analytic ranks translate into an extreme Chebyshev bias. Conversely, we show under a certain linear independence hypothesis on zeros of  $L(E, s)$  that if highly biased elliptic curve prime number races do exist, then the Riemann Hypothesis holds for infinitely many elliptic curve  $L$ -functions and there exist elliptic curves of arbitrarily large rank.

## 1. INTRODUCTION

Let  $E$  be a smooth elliptic curve whose minimal Weierstrass form is

$$E : y^2 + a_1xy + a_3y = x^3 + a_2x^2 + a_4x + a_6 \quad (1)$$

with  $a_i \in \mathbb{Z}$ , and let  $N_E$  denote its conductor. The set of rational points on this curve  $E(\mathbb{Q})$  is a finitely generated abelian group by Mordell's Theorem, and hence is isomorphic to

$$E(\mathbb{Q}) \cong \mathbb{Z}^r \oplus E(\mathbb{Q})_{\text{tors}},$$

where  $E(\mathbb{Q})_{\text{tors}}$  is the finite set of torsion points. Mazur's Theorem [Ma1] gives the list of 15 different possibilities for  $E(\mathbb{Q})_{\text{tors}}$ . As for the integer  $r = r_{\text{al}}(E)$ , the algebraic rank of  $E$ , it is a very mysterious invariant of  $E$ . A central question in number theory is whether  $r_{\text{al}}(E)$  is unbounded as  $E$  varies. The highest rank found so far is due to Elkies [Elk], who explicitly exhibited integer coefficients  $a_1, a_2, a_3, a_4$  and  $a_6$  such that (1) has algebraic rank at least 28. It is conjectured that the set of all ranks of elliptic curves over  $\mathbb{Q}$  is unbounded [B, BS, FGH, U1]. One approach to this conjecture is to study the  $L$ -function of  $E$ . The Birch and Swinnerton-Dyer Conjecture states that  $r_{\text{al}}(E)$  is equal to the order of vanishing of  $L(E, s)$  at  $s = 1$ . Recall that the trace of the Frobenius endomorphism is given for  $p \nmid N_E$  by  $a_p(E) = p + 1 - \#E(\mathbb{F}_p)$ , where  $\#E(\mathbb{F}_p)$  is the number of projective points on the reduction of  $E$  modulo  $p$ . Extending the definition of  $a_p(E)$  to the whole set of primes by setting

$$a_p(E) := \begin{cases} 1 & \text{if } E \text{ has split multiplicative reduction at } p \\ -1 & \text{if } E \text{ has nonsplit multiplicative reduction at } p \\ 0 & \text{if } E \text{ has additive reduction at } p, \end{cases}$$

the  $L$ -function of  $E$  is defined as

$$L(E, s) := \prod_{p|N_E} \left(1 - \frac{a_p(E)}{p^s}\right)^{-1} \prod_{p \nmid N_E} \left(1 - \frac{a_p(E)}{p^s} + \frac{p}{p^{2s}}\right)^{-1}.$$

The Birch and Swinnerton-Dyer Conjecture can be seen as a local-to-global principle, since it asserts that understanding local points on  $E$  is sufficient to understand its algebraic rank, which is a global invariant of  $E$ . Note that the zeros of  $L(E, s)$  come in conjugate pairs and are symmetric about the line  $\Re(s) = 1$ , because of the functional equation relating  $L(E, s)$  to  $L(E, 2 - s)$ .

Considering this, it is of crucial interest to understand the analytic rank  $r_{\text{an}}(E)$ , which by definition is the order of vanishing of  $L(E, s)$  at  $s = 1$ . Our main goal is to establish an equivalence between the conjecture that  $r_{\text{an}}(E)$  is unbounded as  $E$  varies over all elliptic curves over  $\mathbb{Q}$  and a statement about the bias of certain prime number races formed with the local points on  $E$ . This is related to the initial calculations of Birch and Swinnerton-Dyer [BSD1, BSD2], who combined counts of local points on  $E$  to predict its algebraic rank.

Note that if  $r_{\text{an}}(E)$  is unbounded, then it should have a certain growth in terms of conductor, that is there should exist a function  $f(N_E)$  tending to infinity as  $N_E \rightarrow \infty$  such that

$$\limsup_{N_E \rightarrow \infty} \frac{r_{\text{an}}(E)}{f(N_E)} > 0. \quad (2)$$

There are two existing conjectures of this kind in the literature. Ulmer [U1] has shown the existence of non-isotrivial elliptic curves of arbitrarily large rank over the rational function field  $\mathbb{F}_p(t)$  for which the Birch and Swinnerton-Dyer Conjecture holds. His (more general) result shows that Mestre's bound [Me] on ranks of elliptic curves is best possible in the function field case. Based this result, he conjectured<sup>1</sup> [U1, U2] that  $f(N_E) = \log N_E / \log \log N_E$  is admissible in (2). Note that this is also believed to be best possible, since Mestre's conditional bound on ranks of elliptic curves [Me] states that  $r_{\text{an}}(E) \ll \log N_E / \log \log N_E$ . Recently, Farmer, Gonek and Hughes [FGH] have developed a random matrix theory model for predicting the maximal size of the Riemann zeta function on the critical line, which led them to conjecture that

$$\max_{0 \leq t \leq T} |\zeta(\frac{1}{2} + it)| = e^{(1+o(1))\sqrt{\frac{1}{2} \log T \log \log T}}.$$

Their model also suggests that  $f(N_E) = \sqrt{\log N_E \log \log N_E}$  is admissible and best possible in (2).

While the conjectures of Ulmer and Farmer, Gonek and Hughes are incompatible, they both imply the following weaker conjecture.

**Conjecture 1.1.** *We have that*

$$\limsup_{N_E \rightarrow \infty} \frac{r_{\text{an}}(E)}{\sqrt{\log N_E}} = \infty.$$

We now describe the framework in which we relate Conjecture 1.1 to elliptic curve prime number races. Chebyshev's bias is his observation in a letter to Fuss that there seems to be

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<sup>1</sup>Ulmer [U1] makes this conjecture on the algebraic rank, however the Birch and Swinnerton-Dyer Conjecture implies that the corresponding statement on the analytic rank is equivalent.

more primes of the form  $4n + 3$  than of the form  $4n + 1$ . Chebyshev's prime number race is the study of the oscillatory quantity

$$C(x) := \pi(x; 4, 3) - \pi(x; 4, 1),$$

which is known to have infinitely many sign changes [L]. For an account of the rich history of this subject, the reader is referred to the expository article [GM]. Rubinstein and Sarnak [RS] established under GRH and a linear independence hypothesis on the zeros of Dirichlet  $L$ -functions that  $C(e^y)$  is positive for approximately 99.59% of the values of  $y$ . More precisely, they established that

$$\lim_{Y \rightarrow \infty} \frac{\text{meas}\{y \leq Y : C(e^y) > 0\}}{Y} = 0.9959\dots$$

One can study a related quantity by considering local points on an elliptic curve  $E$ . The celebrated Hasse bound states that counting projective points,

$$|\#E(\mathbb{F}_p) - (p + 1)| < 2\sqrt{p}.$$

It is also known that the proportion of primes for which  $a_p(E) = p + 1 - \#E(\mathbb{F}_p)$  is positive is equal to the proportion of primes for which it is negative. In the non-CM case, this follows from the Sato-Tate Conjecture for elliptic curves over  $\mathbb{Q}$ , recently established by Taylor, Clozel, Harris and Shepherd-Barron [T, CHT, HST], which states that when  $E$  has no complex multiplication, the numbers  $a_p(E)/2\sqrt{p}$  are equidistributed in  $[-1, 1]$  with respect to the measure  $(2/\pi)\sqrt{1-t^2}dt$  (the distribution is simpler when  $E$  has complex multiplication). Considering this, Mazur [Ma2] introduced the race between primes for which  $a_p(E) > 0$  and primes for which  $a_p(E) < 0$ . Defining

$$T(t) := \#\{p \leq t : a_p(E) > 0\} - \#\{p \leq t : a_p(E) < 0\},$$

Mazur plotted the graph of  $T(t)$  for various elliptic curves. The reader is encouraged to consult [Ma2] in which several other related quantities are studied. Looking at the graphs appearing in Section 2.3 of [Ma2], one readily sees that  $T(t)$  exhibits a very erratic behaviour. Moreover it is very apparent in these plots that as  $r_{\text{al}}(E)$  increases,  $-T(t)$  becomes more and more biased towards positive values. Indeed, in Figure 2.5 of the paper,  $-T(t)$  does not exhibit any negative value.

Under standard hypotheses, many features of  $T(t)$  were explained by Sarnak [Sa], using the explicit formula for  $L(\text{Sym}^n E, s)$ . Sarnak also introduced a closely related quantity  $S(t)$  defined below, which as he showed can be understood using the explicit formula for  $L(E, s)$  alone. Under a Riemann Hypothesis and a Linear Independence Hypothesis, Sarnak deduced an exact formula for the characteristic function of the limiting distribution of  $ue^{-\frac{u}{2}}S(e^u)$ , and uncovered the direct influence of the analytic rank of  $E$  on this quantity.

Building on the work of Sarnak, we will study the quantity  $S(t)$ , which compares the primes  $p$  for which  $a_p(E) < 0$  against those for which  $a_p(E) > 0$ , weighted by the value of  $a_p(E)/\sqrt{p}$ . This quantity has a very similar behaviour to that of  $-T(t)$ . Moreover, it can be analyzed using  $L(E, s)$  alone [Sa], in contrast to the analysis of  $-T(t)$  which requires hypotheses on symmetric power  $L$ -functions of  $E$ .

We define the elliptic curve prime number race

$$S(t) := - \sum_{p \leq t} \frac{a_p(E)}{\sqrt{p}},$$

and wish to understand the set of  $t$  for which  $S(t) \geq 0$ . To measure the size of this set, that is to measure the bias of  $S(t)$  towards either positive or negative values, we define the following lower and upper logarithmic densities:

$$\underline{\delta}(E) := \liminf_{T \rightarrow \infty} \frac{1}{\log T} \int_{\substack{2 \leq t \leq T \\ S(t) \geq 0}} \frac{dt}{t}, \quad \bar{\delta}(E) := \limsup_{T \rightarrow \infty} \frac{1}{\log T} \int_{\substack{2 \leq t \leq T \\ S(t) \geq 0}} \frac{dt}{t}.$$

If these two densities are equal, then we denote them both by  $\delta(E)$ . Under ECRH and LI(E) (see the definitions below), Sarnak [Sa] has shown that  $\delta(E)$  exists, and differs from  $\frac{1}{2}$ . In other words,  $S(t)$  is always biased. Sarnak also discovered the dependence of this bias on the analytic rank of  $E$ , and a consequence of his results is that under ECRH and LI(E), elliptic curves of analytic rank zero have  $\delta(E) < \frac{1}{2}$  (so  $S(t)$  is biased towards negative values), and elliptic curves of analytic rank  $\geq 1$  have  $\delta(E) > \frac{1}{2}$  (so  $S(t)$  is biased towards positive values).

Our first main result is that Conjecture 1.1 implies that the quantity  $S(t)$  can be arbitrarily biased, under the two following assumptions. Note that the second of these assumption is significantly weaker than the linear independence assumption used in [Sa].

**Hypothesis ECRH** (Elliptic Curve Riemann Hypothesis): *For any elliptic curve  $E$  over  $\mathbb{Q}$ , the non-trivial zeros of  $L(E, s)$  have real part equal to 1.*

**Hypothesis BM** (Bounded Multiplicity): *There exists an absolute constant  $C \geq 1$  such that for any elliptic curve  $E$  over  $\mathbb{Q}$ , the non-real zeros of  $L(E, s)$  have multiplicity at most  $C$ .*

**Theorem 1.2** (Unbounded rank  $\Rightarrow$  arbitrarily biased elliptic curve prime number races). *Assume ECRH and BM, and assume Conjecture 1.1 on the analytic rank of elliptic curves over  $\mathbb{Q}$ . Then for any  $\epsilon > 0$ , there exists an elliptic curve  $E_\epsilon$  over  $\mathbb{Q}$  such that*

$$1 - \epsilon < \underline{\delta}(E_\epsilon) \leq \bar{\delta}(E_\epsilon) < 1.$$

*That is to say, there exists arbitrarily biased elliptic curve prime number races.*

**Remark 1.3.** The proof of Theorem 1.2 does not use the full strength of ECRH and BM. Indeed it is sufficient to assume that these hypotheses hold for an infinite sequence of elliptic curves  $\{E(n)\}_{n \geq 1}$  such that

$$\lim_{n \rightarrow \infty} \frac{r_{\text{an}}(E(n))}{\sqrt{\log N_{E(n)}}} = \infty.$$

Our second main result is a converse result, under a linear independence hypothesis on the zeros of  $L(E, s)$ . We will show that the existence of highly biased elliptic curve prime number races is very strong; under the following assumption, it implies the Riemann Hypothesis for an infinite family of  $L$ -functions as well as the existence of elliptic curves over  $\mathbb{Q}$  of arbitrarily large analytic rank.

**Hypothesis LI(E)** (Linear Independence): *The function  $L(E, s)$  has at least one zero on the line  $\Re(s) = \beta_E := \sup\{\Re(\rho) : L(E, \rho) = 0\}$ . Moreover, the multiset  $Z(E) := \{\Im(\rho) \geq 0 : L(E, \rho) = 0, \Re(\rho) = \beta_E, \rho \neq 1\}$  is linearly independent over  $\mathbb{Q}$ .*

**Remark 1.4.** If the Riemann Hypothesis holds for  $L(E, s)$ , that is  $\beta_E = \sup\{\Re(\rho) : L(E, \rho) = 0\} = 1$ , then Hypothesis LI(E) implies that the multiset of all positive imaginary parts of zeros of  $L(E, s)$  is linearly independent over  $\mathbb{Q}$ . The reason why only positive imaginary parts are considered is that the zeros of  $L(E, s)$  come in conjugate pairs, since

this  $L$ -function is self-dual (because  $a_p(E) \in \mathbb{R}$ ). Also we can potentially have  $L(E, 1) = 0$  (in the case  $\beta_E = 1$ ), and hence it is important not to include this zero in the multiset  $Z(E)$ .

If  $L(E, s)$  has a non-trivial zero outside the critical line  $\Re(s) = 1$ , that is  $\beta_E > 1$ , then one should be careful with the additional symmetry of the set of zeros created by the functional equation. However if  $\rho$  is a zero of  $L(E, s)$ , then the set  $Z(E) = \{\Im(\rho) \geq 0 : L(E, \rho) = 0, \Re(\rho) = \beta_E, \rho \neq 1\}$  contains at most one of the numbers  $\{\rho, \bar{\rho}, 2 - \rho, 2 - \bar{\rho}\}$ .

Note that Hypothesis LI(E) is a hypothesis on the zeros of  $L(E, s)$  lying on the line  $\Re(s) = \beta_E$ . In particular, if the Riemann Hypothesis does not hold for this  $L$ -function, then nothing is assumed on the zeros lying on the critical line.

Finally, note that if  $\beta_E > 1$ , then LI(E) implies that  $L(E, \beta_E) \neq 0$ , since a set containing zero is linearly dependent over  $\mathbb{Q}$ . This is similar to Chowla's Conjecture which states that Dirichlet  $L$ -functions do not vanish for  $s \in (0, 1]$ .

**Theorem 1.5** (Arbitrarily biased elliptic curve prime number races  $\Rightarrow$  unbounded rank). *Assume that there exists a sequence of elliptic curves  $E_n$  over  $\mathbb{Q}$  whose conductor tends to infinity with  $n$ , for which LI( $E_n$ ) holds for  $n \geq 1$  and whose associated prime number race is arbitrarily biased, that is as  $n \rightarrow \infty$ ,*

$$\bar{\delta}(E_n) \rightarrow 1.$$

*Then, there exist elliptic curves over  $\mathbb{Q}$  of arbitrarily large analytic rank. More precisely, Conjecture 1.1 holds.*

**Remark 1.6.** In the proof of Theorem 1.5, we actually show that under LI(E), the bias in  $S(t)$  implies the Riemann Hypothesis for  $L(E, s)$ . The next Theorem is a precise statement of this implication.

**Theorem 1.7** (Biased elliptic curve prime number race  $\Rightarrow$  Riemann Hypothesis). *Assume that LI(E) holds and that either  $\underline{\delta}(E) \neq \frac{1}{2}$  or  $\bar{\delta}(E) \neq \frac{1}{2}$ . Then the Riemann Hypothesis holds for  $L(E, s)$ .*

Theorems 1.5 and 1.7 provide a method to simultaneously probe the Riemann Hypothesis and the unboundedness of the rank of elliptic curves over  $\mathbb{Q}$ . By computing the local points on an elliptic curve  $E$ , one can plot the prime number race  $S(t)$  and if this graph is very biased towards positive values, then this gives evidence towards these two outstanding conjectures. A very strong bias is already present in the quantity  $-T(t)$  associated to the rank three curve  $E : y^2 + y = x^3 - 7x + 6$  appearing in Figure 2.5 of [Ma2].

**Remark 1.8.** One can weaken the second hypothesis of Theorem 1.5 to

$$\limsup_{N_E \rightarrow \infty} \sqrt{\log N_E} (\bar{\delta}(E) - \frac{1}{2}) = \infty,$$

and still deduce the unboundedness of the analytic rank of elliptic curves over  $\mathbb{Q}$ .

## 2. PROOF OF THE NECESSARY CONDITION (THEOREM 1.2)

We start with an outline of the proof of Theorem 1.2. Our strategy is to show that under ECRH, the quantity

$$E(e^y) := -\frac{y}{e^{y/2}} \sum_{p \leq e^y} \frac{a_p(E)}{\sqrt{p}}$$

has a limiting distribution which is the same as the distribution of a certain random variable  $X_E$ . While we do not use this explicitly, one can see that

$$X_E = 2r_{\text{an}}(E) - 1 + \sum_{\gamma > 0} \frac{2\Re(Z_\gamma)}{\frac{1}{4} + \gamma^2},$$

where  $\gamma$  runs over the imaginary parts of the non-trivial zeros of  $L(E, s)$ , and the  $Z_\gamma$  are identically distributed random variables, uniform on the unit circle in  $\mathbb{C}$ . We will then compute the first two moments of  $X_E$ . While the  $Z_\gamma$  are not necessarily independent (unless we assume a linear independence hypothesis), one can show that they have no covariance: if  $\lambda > \gamma > 0$ , then  $\text{Cov}(Z_\gamma, Z_\lambda) = 0$ . This explains the simple formula for the variance appearing in Lemma 2.6. Finally, we will see that if  $r_{\text{an}}(E)$  is significantly larger than  $\sqrt{\log N_E}$ , then the mean of  $X_E$  is significantly larger than its standard deviation, resulting in a very large bias by Chebyshev's inequality.

The fundamental tool we will use is the explicit formula for  $L(E, s)$ . We start with a technical estimate for the tail of a sum over zeros of  $L(E, s + \frac{1}{2})$ .

**Lemma 2.1.** *We have for  $x, T \geq 2$  that*

$$\sum_{|\Im(\rho)| > T} \frac{x^\rho}{\rho} \ll \log x + \frac{x}{T} \left( (\log x)^2 + \frac{\log(TN_E)}{\log x} \right),$$

where  $\rho$  runs over the non-trivial zeros of  $L(E, s + \frac{1}{2})$ .

*Proof.* We first write

$$\begin{aligned} L\left(E, s + \frac{1}{2}\right) &= \prod_{p|N_E} \left(1 - \frac{a_p(E)}{p^{s+\frac{1}{2}}}\right)^{-1} \prod_{p \nmid N_E} \left(1 - \frac{a_p(E)}{p^{s+\frac{1}{2}}} + \frac{1}{p^{2s}}\right)^{-1} \\ &= \prod_{p|N_E} \left(1 - \frac{a_p(E)}{p^{s+\frac{1}{2}}}\right)^{-1} \prod_{p \nmid N_E} \left(1 - \frac{\alpha_p}{p^s}\right)^{-1} \left(1 - \frac{\beta_p}{p^s}\right)^{-1}, \end{aligned}$$

where  $\beta_p = \overline{\alpha_p}$ ,  $|\alpha_p| = |\beta_p| = 1$  and  $\alpha_p + \beta_p = a_p(E)/\sqrt{p}$ . The profound work of Wiles [W], Taylor and Wiles [TW] and Breuil, Conrad, Diamond and Taylor [BCDT] shows that the function  $L(E, s)$  is a modular  $L$ -function, and hence it can be extended to an entire function. Following the proof of Theorem 6.9 of [MV] we obtain using the truncated Perron Formula that for  $x, T \geq 2$ ,

$$\sum_{\substack{p^e \leq x \\ e \geq 1 \\ p \nmid N_E}} (\alpha_p^e + \beta_p^e) \log p + \sum_{\substack{p^e \leq x \\ e \geq 1 \\ p \mid N_E}} \frac{a_p(E)^e}{p^{e/2}} \log p = \int_{\Re(s)=1+\frac{1}{\log x}}_{|\Im(s)| \leq T} \frac{L'(E, s + \frac{1}{2})}{L(E, s + \frac{1}{2})} x^s \frac{ds}{s} + O\left(\log x + \frac{x}{T} (\log x)^2\right).$$

In particular we have that

$$\sum_{\substack{p^e \leq x \\ e \geq 1 \\ p \nmid N_E}} (\alpha_p^e + \beta_p^e) \log p + \sum_{\substack{p^e \leq x \\ e \geq 1 \\ p \mid N_E}} \frac{a_p(E)^e}{p^{e/2}} \log p = \int_{\Re(s)=1+\frac{1}{\log x}} \frac{L'(E, s + \frac{1}{2})}{L(E, s + \frac{1}{2})} x^s \frac{ds}{s} + O(\log x),$$

and hence subtracting these two estimates we obtain

$$\int_{\Re(s)=1+\frac{1}{\log x}, |\Im(s)|>T} \frac{L'(E, s + \frac{1}{2})}{L(E, s + \frac{1}{2})} x^s \frac{ds}{s} \ll \log x + \frac{x}{T} (\log x)^2. \quad (3)$$

Now, if  $s$  is at a distance  $\gg (\log N_E)^{-1}$  from the zeros of  $L(E, s + \frac{1}{2})$ , then (5.27) and (5.28) of [IK] give the bound

$$\frac{L'(E, s + \frac{1}{2})}{L(E, s + \frac{1}{2})} \ll \log(N_E(|\Im(s)| + 2)).$$

Using this bound, (3) becomes

$$\sum_{|\Im(\rho)|>T} \frac{x^\rho}{\rho} + \int_{-\infty < \Re(s) \leq 1+\frac{1}{\log x}, |\Im(s)|=T} \frac{L'(E, s + \frac{1}{2})}{L(E, s + \frac{1}{2})} x^s \frac{ds}{s} \ll \log x + \frac{x}{T} (\log x)^2,$$

where the contour of integration of the last integral should be slightly perturbed to a contour  $C$  which is at a distance  $\gg (\log(N_E T))^{-1}$  from each zero of  $L(E, s)$  (this is possible thanks to the Riemann-von Mangoldt Formula and the zero-free region of  $L(E, s)$ ), and thus

$$\sum_{|\Im(\rho)|>T} \frac{x^\rho}{\rho} \ll \int_C \log(N_E T) x^{\Re(s)} \frac{|ds|}{|s|} + \log x + \frac{x}{T} (\log x)^2 \ll \log x + \frac{x}{T} \left( \frac{\log(N_E T)}{\log x} + (\log x)^2 \right).$$

□

The main tool we will use is the explicit formula (see the corresponding (13) of [Sa]).

**Lemma 2.2.** *Assume the Riemann Hypothesis for  $L(E, s)$ . Then we have for  $x, T \geq 2$  that*

$$E(x) := -\frac{\log x}{\sqrt{x}} \sum_{p \leq x} \frac{a_p(E)}{\sqrt{p}} = 2r_{an}(E) - 1 + \sum_{\gamma_E \neq 0} \frac{e^{i\gamma_E \log x}}{\frac{1}{2} + i\gamma_E} + o_E(1) \quad (4)$$

$$= 2r_{an}(E) - 1 + \sum_{0 < |\gamma_E| \leq T} \frac{e^{i\gamma_E \log x}}{\frac{1}{2} + i\gamma_E} + O\left(\frac{\sqrt{x}}{T} (\log(xTN_E))^2\right) + o_{x \rightarrow \infty}(1), \quad (5)$$

where  $\gamma_E$  runs over the imaginary parts of the non-trivial zeros of  $L(E, s)$ .

*Proof.* We start with the explicit formula for

$$L\left(E, s + \frac{1}{2}\right) = \prod_{p|N_E} \left(1 - \frac{a_p(E)}{p^{s+\frac{1}{2}}}\right)^{-1} \prod_{p \nmid N_E} \left(1 - \frac{\alpha_p}{p^s}\right)^{-1} \left(1 - \frac{\beta_p}{p^s}\right)^{-1},$$

where as before,  $\beta_p = \overline{\alpha_p}$ ,  $|\alpha_p| = |\beta_p| = 1$  and  $\alpha_p + \beta_p = a_p(E)/\sqrt{p}$ . Taking  $T = x$  in (5.53) of [IK] and bounding the rest of the sum over zeros using Lemma 2.1 we obtain the estimate

$$\sum_{\substack{p^e \leq x \\ e \geq 1 \\ p \nmid N_E}} (\alpha_p^e + \beta_p^e) \log p = - \sum_{\gamma_E} \frac{x^{\frac{1}{2} + i\gamma_E}}{\frac{1}{2} + i\gamma_E} + O(\log x \log(xN_E)). \quad (6)$$

Using the trivial bound on the terms on the left-hand side with  $e \geq 3$ , this becomes

$$-x^{-\frac{1}{2}} \sum_{p \leq x} \frac{a_p(E)}{\sqrt{p}} \log p = x^{-\frac{1}{2}} \sum_{p \leq \sqrt{x}} (\alpha_p^2 + \beta_p^2) \log p + 2r_{an}(E) + \sum_{\gamma_E \neq 0} \frac{e^{i\gamma_E \log x}}{\frac{1}{2} + i\gamma_E} + O_E(x^{-\frac{1}{6}}). \quad (7)$$

Now,  $L(\text{Sym}^2 E, s + 1)$  is holomorphic at  $s = 1$ , and a Tauberian argument shows that

$$\sum_{p \leq \sqrt{x}} (\alpha_p^2 + \alpha_p \beta_p + \beta_p^2) \log p = o_E(\sqrt{x}),$$

which combined with (7), the fact that  $\alpha_p \beta_p = 1$  and the Prime Number Theorem gives

$$-x^{-\frac{1}{2}} \sum_{p \leq x} \frac{a_p(E)}{\sqrt{p}} \log p = 2r_{\text{an}}(E) - 1 + \sum_{\gamma_E \neq 0} \frac{e^{i\gamma_E \log x}}{\frac{1}{2} + i\gamma_E} + o_E(1).$$

The estimate (4) follows by a summation by parts as in Lemma 2.1 of [RS], and (5) follows by applying Lemma 2.1.  $\square$

**Lemma 2.3.** *Assume the Riemann Hypothesis for  $L(E, s)$ . Then the quantity  $E(x)$  defined in Lemma 2.2 has a limiting logarithmic distribution, that is there exists a Borel measure  $\mu_E$  on  $\mathbb{R}$  such that for any bounded Lipschitz continuous function  $f : \mathbb{R} \rightarrow \mathbb{R}$  we have*

$$\lim_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y f(E(e^y)) dy = \int_{\mathbb{R}} f(t) d\mu_E(t). \quad (8)$$

*Proof.* This follows from [ANS].  $\square$

**Remark 2.4.** By taking  $f$  to be identically one in (8) we deduce that  $\mu_E(\mathbb{R}) = 1$ , that is  $\mu_E$  is a probability measure.

Let  $X_E$  be the random variable associated to  $\mu_E$ . We will show that the moments of  $E(e^y)$  agree with those of  $X_E$ .

**Lemma 2.5.** *Assume the Riemann Hypothesis for  $L(E, s)$ . We have for  $k \geq 1$  that*

$$\lim_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y E(e^y)^k dy = \int_{\mathbb{R}} t^k d\mu_E(t).$$

*Proof.* We will only prove the  $k = 1$  case since the general result follows along the same lines. Let  $S \geq 1$  and define the bounded Lipschitz continuous function

$$H_S(t) := \begin{cases} 0 & \text{if } |t| \leq S \\ |t| - S & \text{if } S < |t| \leq S + 1 \\ 1 & \text{if } |t| > S + 1. \end{cases}$$

By Lemma 2.3 we have that

$$\lim_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y H_S(E(e^y)) dy = \int_{\mathbb{R}} H_S(t) d\mu_E(t) \leq \mu_E((-\infty, -S] \cup [S, \infty)).$$

In a similar way to Theorem 1.2 of [RS], one can show that  $\mu_E$  has exponentially small tails:

$$\mu_E((-\infty, -S] \cup [S, \infty)) \ll_E \exp(-c_E \sqrt{S}),$$

from which we obtain that

$$\limsup_{Y \rightarrow \infty} \frac{1}{Y} \int_{\substack{2 \leq y \leq Y \\ |E(e^y)| > S+1}} dy \leq \lim_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y H_S(E(e^y)) dy \ll_E \exp(-c_E \sqrt{S}).$$

By using dyadic intervals we easily show that this bound implies

$$\limsup_{Y \rightarrow \infty} \frac{1}{Y} \int_{\substack{2 \leq y \leq Y \\ |E(e^y)| \geq S}} |E(e^y)| dy \ll_E \exp(-c'_E \sqrt{S}). \quad (9)$$

Therefore, defining the bounded Lipschitz continuous function

$$G_S(t) := \begin{cases} t & \text{if } |t| \leq S \\ S(S+1-|t|) & \text{if } S < |t| \leq S+1 \\ 0 & \text{if } |t| > S+1, \end{cases}$$

we obtain using (9) and Lemma 2.3 that

$$\begin{aligned} \limsup_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y E(e^y) dy &= \limsup_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y G_S(E(e^y)) dy + O_E(\exp(-c''_E \sqrt{S})) \\ &= \int_{\mathbb{R}} G_S(t) d\mu_E(t) + O_E(\exp(-c''_E \sqrt{S})) = \int_{\mathbb{R}} t d\mu_E(t) + O_E(\exp(-c'''_E \sqrt{S})), \end{aligned}$$

and so taking  $S \rightarrow \infty$  we obtain that

$$\limsup_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y E(e^y) dy = \int_{\mathbb{R}} t d\mu_E(t).$$

The same argument works for the  $\liminf$ , and hence the assertion is proved.  $\square$

We now explicitly compute the first two moments of  $X_E$ , the random variable associated to the measure  $\mu_E$ . This is analogous to Schlage-Puchta's result [P].

**Lemma 2.6.** *Assume the Riemann Hypothesis for  $L(E, s)$ . Then,*

$$\mathbb{E}[X_E] = 2r_{an}(E) - 1, \quad \text{Var}[X_E] = \sum_{\gamma_E \neq 0}^* \frac{m(\gamma_E)^2}{\frac{1}{4} + \gamma_E^2},$$

where the last sum runs over the imaginary parts of the non-trivial zeros of  $L(E, s)$ , the star meaning that we count the zeros without multiplicity, and  $m(\gamma_E)$  denotes the multiplicity of the zero  $\rho_E = 1 + i\gamma_E$ .

*Proof.* By Lemma 2.2 we have that

$$\begin{aligned} \int_2^Y E(e^y) dy &= (2r_{an}(E) - 1)(Y - 2) + \sum_{\gamma_E \neq 0} \frac{1}{\frac{1}{2} + i\gamma_E} \int_2^Y e^{i\gamma_E y} dy + o(Y) \\ &= (2r_{an}(E) - 1)(Y - 2) + O_E(1) + o(Y), \end{aligned}$$

since the sum  $\sum_{\gamma_E \neq 0} \frac{1}{|\frac{1}{2} + i\gamma_E|^2}$  converges. Taking  $Y \rightarrow \infty$  and applying Lemma 2.5 gives that

$$\mathbb{E}[X_E] = \lim_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y E(e^y) dy = 2r_{an}(E) - 1.$$

As for the second assertion, it follows from Plancherel's identity for Besicovitch  $B^2$  almost-periodic functions. In an effort to be more self-contained we include a proof which follows [P]. We use Lemma 2.2 again. Letting  $\gamma$  and  $\lambda$  run through the ordinates of the non-trivial zeros of  $L(E, s)$ , we have

$$\begin{aligned}
\int_2^Y \left| \sum_{0 < |\gamma_E| \leq T} \frac{e^{i\gamma_E y}}{\frac{1}{2} + i\gamma_E} \right|^2 dy &= \sum_{0 < |\gamma|, |\lambda| \leq T}^* \frac{m(\gamma)m(\lambda)}{(\frac{1}{2} + i\gamma)(\frac{1}{2} - i\lambda)} \int_2^Y e^{iy(\gamma - \lambda)} dy \\
&= (Y - 2) \sum_{0 < |\gamma_E| \leq T}^* \frac{m(\gamma_E)^2}{\frac{1}{4} + \gamma_E^2} + O \left( \sum_{\substack{0 < |\gamma|, |\lambda| \leq T \\ \gamma \neq \lambda}} \frac{\min\{Y, |\gamma - \lambda|^{-1}\}}{(1 + |\gamma|)(1 + |\lambda|)} \right).
\end{aligned}$$

(Note that we have removed the star in the sum in the error term, which explains why the multiplicities disappeared.) The first sum converges absolutely, since the Riemann-von Mangoldt formula (see Theorem 5.8 of [IK])

$$N(T, E) := \#\{\gamma_E : 0 \leq \gamma_E \leq T\} = \frac{T}{2\pi} \log \left( \frac{N_E T}{2\pi e} \right) + O(\log(N_E T))$$

implies that  $m(\gamma_E) \ll \log(N_E(3 + |\gamma_E|))$ . Introducing a parameter  $1 \leq U < T$ , the sum appearing in the error term is at most:

$$\begin{aligned}
&\sum_{\substack{0 < |\gamma|, |\lambda| \leq T \\ |\gamma - \lambda| \geq 1}} \frac{|\gamma - \lambda|^{-1}}{(1 + |\gamma|)(1 + |\lambda|)} + \sum_{\substack{U < |\gamma|, |\lambda| \leq T \\ |\gamma - \lambda| \leq 1}} \frac{Y}{(1 + |\gamma|)(1 + |\lambda|)} + \sum_{\substack{0 < |\gamma|, |\lambda| \leq U \\ 0 < |\gamma - \lambda| \leq 1}} \frac{|\gamma - \lambda|^{-1}}{(1 + |\gamma|)(1 + |\lambda|)} \\
&\ll_E \sum_{\substack{\gamma, \lambda \\ |\gamma - \lambda| \geq 1}} \frac{|\gamma - \lambda|^{-1}}{(1 + |\gamma|)(1 + |\lambda|)} + Y \sum_{U \leq |\gamma| \leq T} \frac{\log |\gamma|}{(1 + |\gamma|)^2} + S(U) \\
&\ll_E 1 + Y \frac{(\log U)^2}{U} + S(U),
\end{aligned} \tag{10}$$

since the integral  $\iint_{|x-y| \geq 1} \frac{|x-y|^{-1} \log x \log y}{(|x|+1)(|y|+1)} dx dy$  converges. Here,

$$S(U) := \sum_{\substack{0 < |\gamma|, |\lambda| \leq U \\ 0 < |\gamma - \lambda| \leq 1}} \frac{|\gamma - \lambda|^{-1}}{(1 + |\gamma|)(1 + |\lambda|)}.$$

Define  $Y_U \geq U^2$  to be an increasing function of  $U$  such that for each  $U \geq 1$ ,  $US(U) \leq Y_U$  (this is ineffective). Inverting this process, we find an increasing function  $U(Y) \leq \sqrt{Y}$  such that  $U(Y) \rightarrow \infty$  as  $Y \rightarrow \infty$ , and such that for  $Y$  large enough,  $U(Y)S(U(Y)) \leq Y$ . This shows that (10) is

$$\ll 1 + Y \frac{(\log U(Y))^2}{U(Y)} + \frac{Y}{U(Y)} = o_{Y \rightarrow \infty}(Y).$$

That is, we have shown that

$$\int_2^Y \left| \sum_{0 < |\gamma_E| \leq T} \frac{e^{i\gamma_E y}}{\frac{1}{2} + i\gamma_E} \right|^2 dy = (Y - 2) \sum_{0 < |\gamma_E| \leq T}^* \frac{m(\gamma_E)^2}{\frac{1}{4} + \gamma_E^2} + o_{Y \rightarrow \infty}(Y).$$

Therefore, by Lemma 2.2 we obtain by taking  $T = e^{2Y}$  that

$$\begin{aligned}
\int_2^Y |E(e^y) - \mathbb{E}[X_E]|^2 dy &= \int_2^Y \left| \sum_{0 < |\gamma_E| \leq e^{2Y}} \frac{e^{i\gamma_E y}}{\frac{1}{2} + i\gamma_E} \right|^2 dy \\
&\quad + O_E \left( \int_2^Y \left| \sum_{0 < |\gamma_E| \leq e^{2Y}} \frac{e^{i\gamma_E y}}{\frac{1}{2} + i\gamma_E} \right| o_{y \rightarrow \infty}(1) dy + o_{Y \rightarrow \infty}(Y) \right) \\
&= (Y-2) \sum_{0 < |\gamma_E| \leq e^{2Y}}^* \frac{m(\gamma_E)^2}{\frac{1}{4} + \gamma_E^2} + o_{Y \rightarrow \infty}(Y),
\end{aligned}$$

by the Cauchy-Schwartz inequality. The result follows by taking  $Y \rightarrow \infty$  and applying Lemma 2.5.  $\square$

**Lemma 2.7.** *Assume the Riemann Hypothesis for  $L(E, s)$ . If*

$$B(E) := \frac{\mathbb{E}[X_E]}{\sqrt{\text{Var}[X_E]}}$$

*is large enough, then*

$$\underline{\delta}(E) \geq 1 - 2 \frac{\text{Var}[X_E]}{\mathbb{E}[X_E]^2}.$$

*Proof.* It is clear from Lemma 2.6 and the Riemann-von Mangoldt formula that  $\text{Var}[X_E] \gg \log N_E$ , and therefore our assumption that  $B(E)$  is large enough implies that  $\mathbb{E}[X_E]$  is also large enough, say at least 4. Let now

$$H(x) := \begin{cases} 1 & \text{if } x \geq 0 \\ 0 & \text{if } x < 0, \end{cases} \quad f(x) := \begin{cases} 1 & \text{if } x \geq 1 \\ x & \text{if } 0 \leq x \leq 1 \\ 0 & \text{if } x < 0. \end{cases}$$

Clearly,  $f(x)$  is bounded Lipschitz continuous and  $f(x) \leq H(x)$ . Therefore,

$$\underline{\delta}(E) = \liminf_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y H(E(e^y)) dy \geq \liminf_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y f(E(e^y)) dy,$$

which by Lemma 2.3 is equal to

$$\begin{aligned}
\int_{\mathbb{R}} f(t) d\mu_E(t) &= 1 - \int_{\mathbb{R}} (1 - f(t)) d\mu_E(t) \\
&= 1 - \int_{-\infty}^1 (1 - f(t)) d\mu_E(t) \geq 1 - \mu_E(-\infty, 1].
\end{aligned}$$

We now apply Chebyshev's inequality:

$$\begin{aligned}
\mu_E(-\infty, 1] &= \text{Prob}[X_E \leq 1] = \text{Prob}[X_E - \mathbb{E}[X_E] \leq 1 - \mathbb{E}[X_E]] \\
&\leq \text{Prob}[|X_E - \mathbb{E}[X_E]| \geq \mathbb{E}[X_E] - 1] \leq \frac{\text{Var}[X_E]}{(\mathbb{E}[X_E] - 1)^2} \leq 2 \frac{\text{Var}[X_E]}{\mathbb{E}[X_E]^2}
\end{aligned}$$

since  $\mathbb{E}[X_E] \geq 4$ , and therefore

$$\underline{\delta}(E) \geq 1 - 2 \frac{\text{Var}[X_E]}{\mathbb{E}[X_E]^2}.$$

□

We are now ready to prove Theorem 1.2.

*Proof of Theorem 1.2.* Let  $X_E$  be the random variable associated to the measure  $\mu_E$ . By Lemma 2.6, its mean is equal to  $\mathbb{E}[X_E] = 2r_{\text{an}}(E) - 1$ , and by our assumption that the non-real zeros of  $L(E, s)$  have bounded multiplicity we have

$$\sum_{\gamma_E \neq 0} \frac{1}{\frac{1}{4} + \gamma_E^2} \leq \text{Var}[X_E] = \sum_{\gamma_E \neq 0}^* \frac{m(\gamma_E)^2}{\frac{1}{4} + \gamma_E^2} \ll \sum_{\gamma_E \neq 0} \frac{1}{\frac{1}{4} + \gamma_E^2},$$

and thus by the Riemann-von Mangoldt formula,

$$\text{Var}[X_E] \asymp \log N_E.$$

The condition

$$\limsup_{N_E \rightarrow \infty} \frac{r_{\text{an}}(E)}{\sqrt{\log N_E}} = \infty$$

then implies that

$$\limsup_{N_E \rightarrow \infty} \frac{\mathbb{E}[X_E]}{\sqrt{\text{Var}[X_E]}} = \infty.$$

Combining this with Lemma 2.7 shows that

$$\sup_E \underline{\delta}(E) = 1.$$

The last thing to show is that  $\bar{\delta}(E) < 1$  for all elliptic curves, however this follows from an analysis as in Lemma 2.7 combined with a lower bound on  $\mu_E(-\infty, -1]$  similar to that in Theorem 1.2 of [RS], which can be derived using similar techniques.

□

### 3. PROOF OF THE SUFFICIENT CONDITION (THEOREM 1.5)

The first step will be to show that under the first assumption in Theorem 1.5, the quantity

$$E_n(x) := -\frac{\log x}{x^{\beta_n - \frac{1}{2}}} \sum_{p \leq x} \frac{a_p(E_n)}{\sqrt{p}}$$

has a limiting logarithmic distribution as  $x \rightarrow \infty$ .

**Lemma 3.1.** *Fix  $T \geq 1$  and assume that  $L(E, s)$  has at least one zero on the line  $\Re(s) = \beta_0 := \sup\{\Re(z) : L(E, z) = 0\}$ . Then letting  $\rho$  run over the non-trivial zeros of  $L(E, s + \frac{1}{2})$  we have that the quantity*

$$F_T(x) := x^{-\beta_0 + \frac{1}{2}} \sum_{\substack{\rho \\ |\Im(\rho)| \leq T}} \frac{x^\rho}{\rho} - x^{1-\beta_0}$$

has a limiting logarithmic distribution as  $x \rightarrow \infty$ , that is there exists a Borel measure  $\mu_E^{(T)}$  such that for every bounded Lipschitz continuous function  $f$  we have

$$\lim_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y f(F_T(e^y)) dy = \int_{\mathbb{R}} f(t) d\mu_E^{(T)}(t).$$

**Remark 3.2.** Since the non-trivial zeros of  $L(E, s)$  are symmetric about the line  $\Re(s) = 1$ , we always have  $\beta_0 \geq 1$ . The Riemann Hypothesis for  $L(E, s)$  states that  $\beta_0 = 1$ .

*Proof of Lemma 3.1.* Define  $\beta_T := \sup\{\Re(z) : L(E, z) = 0, |\Im(z)| \leq T, \Re(z) < \beta_0\}$ , which is strictly less than  $\beta_0$  since  $L(E, s)$  has only finitely many zeros of height at most  $T$ . We have by the Riemann-von Mangoldt Formula that

$$F_T(x) = \sum_{\substack{\rho \\ \Re(\rho)=\beta_0-\frac{1}{2} \\ |\Im(\rho)| \leq T}} \frac{x^{i\gamma}}{\rho} - x^{1-\beta_0} + O_E(x^{-\delta_T} (\log T)^2), \quad (11)$$

where  $\delta_T = \beta_0 - \beta_T > 0$  and  $\rho = \eta + i\gamma$  runs over the non-trivial zeros of  $L(E, s + \frac{1}{2})$ . Hence, the limiting logarithmic distribution of  $F_T(x)$  coincides with the limiting distribution of

$$G_T(y) := -\epsilon(\beta_0) + \sum_{\substack{\rho \\ \Re(\rho)=\beta_0-\frac{1}{2} \\ |\Im(\rho)| \leq T}} \frac{e^{i\gamma y}}{\rho},$$

which exists by arguments analogous to Lemma 2.3 of [RS]. Here,

$$\epsilon(\beta_0) := \begin{cases} 1 & \text{if } \beta_0 = 1 \\ 0 & \text{otherwise.} \end{cases}$$

□

We now adapt Lemma 2.2 of [RS].

**Lemma 3.3.** *Let*

$$\epsilon(x; T) := x^{-\beta_0+\frac{1}{2}} \sum_{\substack{\rho \\ |\Im(\rho)| > T}} \frac{x^\rho}{\rho},$$

where  $\beta_0 = \sup\{\Re(z) : L(E, z) = 0\}$  and  $\rho$  runs over the non-trivial zeros of  $L(E, s + \frac{1}{2})$ . Then we have for  $T \geq 1$  and  $Y \geq 2$  that

$$\int_2^Y |\epsilon(e^y; T)|^2 dy \ll_E Y \frac{(\log T)^2}{T} + \frac{(\log T)^3}{T}.$$

*Proof.* We compute

$$\begin{aligned} \int_2^Y |\epsilon(e^y; T)|^2 dy &= \sum_{\substack{\rho_1, \rho_2 \\ |\Im(\rho_1)|, |\Im(\rho_2)| > T}} \int_2^Y \frac{e^{y(\rho_1 + \bar{\rho}_2 - 2\beta_0 + 1)}}{\rho_1 \bar{\rho}_2} dy \\ &\ll_E \sum_{\substack{\rho_1, \rho_2 \\ |\Im(\rho_1)|, |\Im(\rho_2)| > T}} \frac{1}{|\Im(\rho_1)| |\Im(\rho_2)|} \min(Y, |\rho_1 + \bar{\rho}_2 - 2\beta_0 + 1|^{-1}), \end{aligned}$$

since one can easily show that for any  $s \in \mathbb{C}$  with  $\Re(s) \leq 0$ ,

$$\left| \int_2^Y e^{sy} dy \right| \leq \min(2|s|^{-1}, Y).$$

The proof follows as in Lemma 2.2 of [RS] since  $|\rho_1 + \bar{\rho}_2 - 2\beta_0 + 1|^{-1} \leq |\Im(\rho_1) - \Im(\rho_2)|^{-1}$ .  $\square$

**Lemma 3.4.** *Assume that  $L(E, s)$  has at least one zero on the line  $\Re(s) = \beta_0 := \sup\{\Re(z) : L(E, z) = 0\} \geq 1$ . Then the quantity*

$$E(x) := -\frac{\log x}{x^{\beta_0 - \frac{1}{2}}} \sum_{p \leq x} \frac{a_p(E)}{\sqrt{p}}$$

has a limiting logarithmic distribution  $\mu_E$  as  $x \rightarrow \infty$ .

*Proof.* We argue as in Lemma 2.2. Defining  $\alpha_p$  and  $\beta_p$  as we did in this lemma we have by (5.53) of [IK] that for  $1 \leq U \leq x$  (see the corresponding (13) of [Sa]),

$$\sum_{\substack{p^e \leq x \\ e \geq 1 \\ p \nmid N_E}} (\alpha_p^e + \beta_p^e) \log p = - \sum_{|\Im(\rho)| \leq U} \frac{x^\rho}{\rho} + O\left(\frac{x}{U} \log x \log(N_E x)\right),$$

where  $\rho$  runs over the non-trivial zeros of  $L(E, s + \frac{1}{2})$ , and hence

$$\begin{aligned} -x^{-\beta_0 + \frac{1}{2}} \sum_{p \leq x} \frac{a_p(E)}{\sqrt{p}} \log p &= x^{-\beta_0 + \frac{1}{2}} \sum_{p \leq \sqrt{x}} (\alpha_p^2 + \beta_p^2) \log p + x^{-\beta_0 + \frac{1}{2}} \sum_{|\Im(\rho)| \leq U} \frac{x^\rho}{\rho} \\ &\quad + O_E\left(\frac{x^{\frac{3}{2} - \beta_0}}{U} \log x \log(N_E x) + x^{\frac{5}{6} - \beta_0}\right). \end{aligned}$$

As in Lemma 2.2, combining this with a Tauberian argument on  $L(\text{Sym}^2 E, s + 1)$  and a summation by parts gives that

$$E(x) = x^{-\beta_0 + \frac{1}{2}} \sum_{|\Im(\rho)| \leq U} \frac{x^\rho}{\rho} - x^{1 - \beta_0} + O_E\left(\frac{x^{\frac{3}{2} - \beta_0}}{U} (\log x)^2\right) + o_{x \rightarrow \infty}(1),$$

and so taking  $U = x$ , using that  $\beta_0 \geq 1$ , and applying Lemma 2.1 we obtain that for any  $T \geq 1$ ,

$$E(x) = x^{-\beta_0 + \frac{1}{2}} \sum_{\rho} \frac{x^\rho}{\rho} - x^{1 - \beta_0} + o_{x \rightarrow \infty}(1) = F_T(x) + \epsilon(x; T) + o_{x \rightarrow \infty}(1),$$

where  $F_T(x)$  and  $\epsilon(x; T)$  are defined in Lemmas 3.1 and 3.3 respectively.

Let now  $f$  be a bounded Lipschitz continuous function. We have as in Section 2.1 of [RS] that

$$\begin{aligned} \frac{1}{Y} \int_2^Y f(E(e^y)) dy &= \frac{1}{Y} \int_2^Y f(F_T(e^y)) dy + O_f \left( \frac{1}{Y} \int_2^Y |\epsilon(e^y; T)| dy \right) + o_{Y \rightarrow \infty}(1) \\ &= \frac{1}{Y} \int_2^Y f(F_T(e^y)) dy + O_f \left( \frac{1}{\sqrt{Y}} \left( \int_2^Y |\epsilon(e^y; T)|^2 dy \right)^{\frac{1}{2}} \right) + o_{Y \rightarrow \infty}(1) \\ &= \frac{1}{Y} \int_2^Y f(F_T(e^y)) dy + O_f \left( \frac{\log T}{\sqrt{T}} + \frac{(\log T)^{\frac{3}{2}}}{\sqrt{TY}} \right) + o_{Y \rightarrow \infty}(1) \end{aligned}$$

by the Cauchy-Schwartz inequality and Lemma 3.3. Taking  $Y \rightarrow \infty$  and using that  $F_T(e^y)$  has a limiting distribution (Lemma 3.1) we obtain

$$\begin{aligned} \int_{\mathbb{R}} f(x) d\mu_E^{(T)}(x) - O \left( \frac{\log T}{\sqrt{T}} \right) &\leq \liminf_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y f(E(e^y)) dy \\ &\leq \limsup_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y f(E(e^y)) dy \leq \int_{\mathbb{R}} f(x) d\mu_E^{(T)}(x) + O \left( \frac{\log T}{\sqrt{T}} \right). \quad (12) \end{aligned}$$

As in [ANS], we apply Helly's Theorem to the sequence of probability measures  $\{\mu_E^{(T)}\}_{T \geq 1}$ ; this ensures the existence of a subsequence  $\{\mu_E^{(T_k)}\}_{k \geq 1}$  which converges weakly to a limiting probability measure  $\mu_E$  (since  $\mu_E^{(T_k)}(\mathbb{R}) = 1$ ). The estimate (12) then shows that  $\mu_E^{(T)}$  converges weakly to  $\mu_E$  as  $T \rightarrow \infty$ , and thus

$$\limsup_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y f(E(e^y)) dy = \liminf_{Y \rightarrow \infty} \frac{1}{Y} \int_2^Y f(E(e^y)) dy = \int_{\mathbb{R}} f(x) d\mu_E(x).$$

□

**Remark 3.5.** Alternatively, we could have concluded the existence of a limiting distribution by applying Lemma 1.11 of [Ell], which asserts that if  $\hat{\mu}_E^{(T)}(\xi)$  converges to a function uniformly in all compact subsets of  $\mathbb{R}$ , then  $\mu_E^{(T)}$  converges weakly to a probability measure. We will see in Lemma 3.6 that (see also (21) of [Sa])

$$\hat{\mu}_E^{(T)}(\xi) = e^{i\xi(2r_{\text{an}}(E)-1)\epsilon(\beta_0)} \prod_{\substack{\rho \\ \Re(\rho)=\beta_0-\frac{1}{2} \\ 0 < \Im(\rho) \leq T}} J_0 \left( \frac{2\xi}{|\rho|} \right),$$

which converges absolutely and uniformly in any compact subset of  $\mathbb{R}$  to the function on the right-hand side of (13).

In the next lemma we give an explicit description of the Fourier Transform of  $\mu_E$ , which corresponds to (21) of [Sa].

**Lemma 3.6.** *Assume that  $L(E, s)$  has at least one zero on the line  $\Re(s) = \beta_0 := \sup\{\Re(z) : L(E, z) = 0\}$  and assume that the set  $\{\Im(z) \geq 0 : L(E, z) = 0, \Re(z) = \beta_0, z \neq 1\}$  is linearly*

independent over  $\mathbb{Q}$ . Then the Fourier Transform of  $\mu_E$  is given by

$$\hat{\mu}_E(\xi) = e^{i\xi(2r_{\text{an}}(E)-1)\epsilon(\beta_0)} \prod_{\substack{\rho \\ \Re(\rho)=\beta_0-\frac{1}{2} \\ \Im(\rho)>0}} J_0\left(\frac{2\xi}{|\rho|}\right), \quad (13)$$

where  $\rho$  runs over the non-trivial zeros of  $L(E, s + \frac{1}{2})$  and

$$\epsilon(\beta_0) := \begin{cases} 1 & \text{if } \beta_0 = 1 \\ 0 & \text{otherwise.} \end{cases}$$

*Proof.* We first compute the Fourier Transform of  $\mu_E^{(T)}$ . Note that the assumption that the set  $\{\Im(z) : L(E, z) = 0, \Re(z) = \beta_0, z \neq 1\}$  is linearly independent over  $\mathbb{Q}$  implies that if  $\beta_0 > 1$ , then  $L(E, \beta_0) \neq 0$ . Hence, (11) becomes

$$F_T(x) = (2r_{\text{an}}(E) - 1)\epsilon(\beta_0) + \sum_{\substack{\rho \\ \Re(\rho)=\beta_0-\frac{1}{2} \\ 0<|\Im(\rho)|\leq T}} \frac{x^{i\rho}}{\rho} + o_{x \rightarrow \infty}(1) + O_E(x^{-\delta_T}(\log T)^2),$$

where  $\rho$  runs over the non-trivial zeros of  $L(E, s + \frac{1}{2})$ . Now, since  $\mu_E^{(T)}$  is the limiting distribution of  $F_T(e^y)$  by Lemma 3.1, we deduce by classical arguments (see for instance the proof of Proposition 2.13 of [FiMa]) that

$$\hat{\mu}_E^{(T)}(\xi) = e^{i\xi(2r_{\text{an}}(E)-1)\epsilon(\beta_0)} \prod_{\substack{\rho \\ \Re(\rho)=\beta_0-\frac{1}{2} \\ 0<\Im(\rho)\leq T}} J_0\left(\frac{2\xi}{|\rho|}\right).$$

The proof follows from the fact that the measures  $\mu_E^{(T)}$  converge weakly to  $\mu_E$  (this was established in the proof of Lemma 3.4), and thus Lévy's criterion implies that  $\hat{\mu}_E^{(T)}(\xi) \rightarrow \hat{\mu}_E(\xi)$  pointwise (see Lemma 1.11 of [Ell]).  $\square$

We are now ready to prove Theorem 1.5.

*Proof of Theorem 1.5.* Let  $\{E_n\}_{n \geq 1}$  be a sequence of elliptic curves over  $\mathbb{Q}$  for which  $\text{LI}(E_n)$  holds and for which as  $n \rightarrow \infty$ ,

$$\bar{\delta}(E_n) \rightarrow 1.$$

Assume also that the Riemann Hypothesis does not hold for  $L(E_n, s)$ , that is  $\beta_n := \sup\{\Re(z) : L(E_n, z) = 0\} > 1$ , for arbitrarily large values of  $n$ . By Lemmas 3.4 and 3.6, the quantity

$$E_n(x) := -\frac{\log x}{x^{\beta_n-\frac{1}{2}}} \sum_{p \leq x} \frac{a_p(E_n)}{\sqrt{p}}$$

has a limiting logarithmic distribution  $\mu_{E_n}$  whose Fourier transform is given, for the values of  $n$  for which  $\beta_n > 1$ , by

$$\hat{\mu}_{E_n}(\xi) = \prod_{\substack{\rho \\ \Re(\rho)=\beta_n-\frac{1}{2} \\ \Im(\rho)>0}} J_0\left(\frac{2\xi}{|\rho|}\right), \quad (14)$$

where  $\rho$  runs over the non-trivial zeros of  $L(E_n, s + \frac{1}{2})$ . This implies that the limiting distribution of  $E_n(e^y)$  is continuous, that is  $\mu_{E_n}$  is absolutely continuous with respect to Lebesgue measure. Indeed, if  $L(E_n, s + \frac{1}{2})$  has a finite number of zeros  $\rho$  on the line  $\Re(\rho) = \beta_n - \frac{1}{2}$ , then the bound  $|J_0(x)| \leq \min(1, (\pi|x|/2)^{-\frac{1}{2}})$  (see (4.5) of [RS]) implies that for  $\xi \gg_n 1$ ,

$$|\hat{\mu}_{E_n}(\xi)| \leq \prod_{\substack{\rho \\ \Re(\rho)=\beta_n-\frac{1}{2} \\ \Im(\rho)>0}} (\pi|\xi|/|\rho|)^{-\frac{1}{2}} \ll_n |\xi|^{-\frac{1}{2}},$$

and thus combining this with the bound  $|\hat{\mu}_{E_n}(\xi)| \leq 1$ , the absolute continuity of  $\mu_{E_n}$  follows by applying Lemma 1.23 of [Ell]. As for the case where  $L(E_n, s + \frac{1}{2})$  has infinitely many zeros  $\rho$  on the line  $\Re(\rho) = \beta_n - \frac{1}{2}$ , we have by adapting the proof of Lemma 2.16 of [FiMa] that for  $\xi \gg_n 1$ ,

$$|\hat{\mu}_{E_n}(\xi)| \leq \prod_{\substack{\rho \\ \Re(\rho)=\beta_n-\frac{1}{2} \\ 0<\Im(\rho)<|\xi|/2-1}} (\pi|\xi|/|\rho|)^{-\frac{1}{2}} \leq 2^{-\#\{\rho: \Re(\rho)=\beta_n-\frac{1}{2}, 0<\Im(\rho)<|\xi|/2-1\}/2} = o_{|\xi|\rightarrow\infty}(1),$$

and once more the absolute continuity of  $\mu_{E_n}$  follows by applying Lemma 1.23 of [Ell].

Now,  $J_0(t)$  is an even function, and thus so is  $\hat{\mu}_{E_n}(\xi)$  by (14). Since  $\hat{\mu}_{E_n}(\xi)$  is also real for real  $\xi$ , this implies that  $\mu_{E_n}$  is symmetrical, and hence for arbitrarily large values of  $n$  we have by absolute continuity of  $\mu_{E_n}$  that

$$\bar{\delta}(E_n) = \underline{\delta}(E_n) = \delta(E_n) = \mu_{E_n}([0, \infty)) = \frac{1}{2},$$

contradicting our assumption that  $\delta(E_n) \rightarrow 1$  as  $n$  tends to infinity. Having reached a contradiction, we deduce that for all large enough values of  $n$ , the Riemann Hypothesis holds for  $L(E_n, s)$ .

We now show the existence of elliptic curves of arbitrarily large rank. Assume that Conjecture 1.1 is false, that is for all elliptic curves  $E$  over  $\mathbb{Q}$ ,

$$r_{\text{an}}(E) \ll \sqrt{\log N_E}.$$

We know that the Riemann Hypothesis holds for  $L(E_n, s)$  for large enough  $n$ , and hence all of the lemmas of Section 2 hold. In particular, taking  $E$  to be any of these curves and denoting by  $X_E$  the random variable associated with  $\mu_E$ , we have by Lemma 2.6 that

$$\mathbb{E}[X_E] = 2r_{\text{an}}(E) - 1, \quad \text{Var}[X_E] = \sum_{\gamma_E \neq 0} \frac{1}{\frac{1}{4} + \gamma_E^2} \asymp \log N_E, \quad (15)$$

(see (27)-(29) of [Sa]) since the assumption  $\text{LI}(E)$  implies that the non-real zeros of  $L(E, s)$  are simple. Moreover, the Riemann hypothesis for  $L(E, s)$  implies that we have  $\rho = \frac{1}{2} + i\gamma$

in Lemma 3.6, that is

$$\hat{\mu}_E(\xi) = e^{i\xi(2r_{\text{an}}(E)-1)} \prod_{\substack{\rho \\ \Im(\rho)>0}} J_0 \left( \frac{2\xi}{\sqrt{\frac{1}{4} + \Im(\rho)^2}} \right).$$

Defining

$$Y_E := \frac{X_E - \mathbb{E}[X_E]}{\sqrt{\text{Var}[X_E]}},$$

where  $X_E$  is the random variable associated with the measure  $\mu_E$ , we have by the analyticity of  $\log J_0(z)$  in the disk<sup>2</sup>  $|z| \leq \frac{12}{5}$  that taking Taylor series in the range  $|t| \leq \sqrt{\text{Var}[X_E]}$ ,

$$\begin{aligned} \log \hat{Y}_E(t) &= \sum_{\substack{\rho \\ \Im(\rho)>0}} \log J_0 \left( \frac{2t}{\sqrt{\text{Var}[X_E]}\sqrt{\frac{1}{4} + \Im(\rho)^2}} \right) \\ &= -\frac{(2t)^2}{4\text{Var}[X_E]} \sum_{\substack{\rho \\ \Im(\rho)>0}} \frac{1}{\frac{1}{4} + \Im(\rho)^2} + O \left( \frac{t^4}{(\log N_E)^2} \sum_{\substack{\rho \\ \Im(\rho)>0}} \frac{1}{\left(\frac{1}{4} + \Im(\rho)^2\right)^2} \right) \\ &= -\frac{t^2}{2} + O \left( \frac{t^4}{\log N_E} \right), \end{aligned}$$

by the Riemann-von Mangoldt Formula. Hence,  $\hat{Y}_E(t) \rightarrow e^{-t^2/2}$  pointwise as  $N_E \rightarrow \infty$ , and thus Lévy's criterion (see Lemma 1.11 of [Ell]) implies that  $Y_E$  converges weakly to a Gaussian distribution. By the absolute continuity of  $\mu_E$ , we have that  $\delta(E)$  exists, and

$$\delta(E) = \text{Prob}[X_E > 0] = \text{Prob}[Y_E > -\mathbb{E}[X_E]/\sqrt{\text{Var}[X_E]}].$$

Therefore, the assumption that  $r_{\text{an}}(E) \ll \sqrt{\log N_E}$  and (15) imply that this last quantity is

$$\leq \text{Prob}[Y_E > -C],$$

for some absolute constant  $C$ . By the central limit theorem we just proved, this quantity tends to

$$\frac{1}{\sqrt{2\pi}} \int_{-C}^{\infty} e^{-\frac{t^2}{2}} dt < 1$$

as  $N_E \rightarrow \infty$ . Therefore, we obtain the bound

$$\limsup_{N_E \rightarrow \infty} \delta(E) \leq \frac{1}{\sqrt{2\pi}} \int_{-C}^{\infty} e^{-\frac{t^2}{2}} dt < 1,$$

which contradicts our assumption that  $\delta(E_n) = \bar{\delta}(E_n) \rightarrow 1$  as  $n \rightarrow \infty$ . Having reached a contradiction, we conclude that Conjecture 1.1 holds.  $\square$

*Proof of Theorem 1.7.* Following the steps of the proof of Theorem 1.5, one sees that if  $\text{LI}(E)$  holds and  $\beta_E > 1$ , then by the symmetry and absolute continuity of  $\mu_E$  we have

$$\bar{\delta}(E_n) = \underline{\delta}(E_n) = \delta(E_n) = \mu_{E_n}([0, \infty)) = \frac{1}{2}.$$

Hence, we have proved the contrapositive Theorem 1.7.  $\square$

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<sup>2</sup>The function  $\log J_0(z)$  is holomorphic in the disc  $|z| < x_0$ , where  $x_0 = 2.4048\dots$  is the first zero of  $J_0(z)$ .

**Remark 3.7.** One can weaken the second hypothesis of Theorem 1.5 to

$$\limsup_{N_E \rightarrow \infty} \sqrt{\log N_E} (\overline{\delta}(E) - \frac{1}{2}) = \infty,$$

and still conclude the unboundedness of the analytic rank of elliptic curves over  $\mathbb{Q}$ .

## APPENDIX A. COMPARISON OF CONJECTURES ON LARGE RANKS OF ELLIPTIC CURVES

We conclude the paper with a numerical study of Conjecture 1.1, comparing the conjectures of Ulmer and Farmer, Gonek and Hughes. In this section we assume the Birch and Swinnerton-Dyer Conjecture, that is  $r_{\text{an}}(E) = r_{\text{al}}(E)$  for every elliptic curve  $E$  over  $\mathbb{Q}$ .

Mestre [Me] has shown that

$$r_{\text{an}}(E) \ll \log N_E,$$

and under ECRH,

$$r_{\text{an}}(E) \ll \frac{\log N_E}{\log \log N_E}. \quad (16)$$

For elliptic curves over function fields, Ulmer has shown that the analogue of (16) is best possible, and thus he conjectured that (16) is also best possible for elliptic curves over  $\mathbb{Q}$  [U1, U2]. Elkies and Watkins [EW] have given numerical evidence for Ulmer's conjecture by finding elliptic curves having large rank and moderate conductor. They mention that numerical data shows that the statement

$$0 < \limsup_{N_E \rightarrow \infty} \frac{r_{\text{an}}(E)}{\log N_E / \log \log N_E} < \infty \quad (17)$$

is quite likely to be true. A few years later, Farmer, Gonek and Hughes [FGH] constructed a random matrix model which suggests the conjecture

$$0 < \limsup_{N_E \rightarrow \infty} \frac{r_{\text{an}}(E)}{\sqrt{\log N_E \log \log N_E}} < \infty. \quad (18)$$

Interestingly, Elkies and Watson's numerical data supports both (17) and (18). The reason for this is that the quotient between the two conjectures, that is

$$f(N_E) := \frac{(\log N_E)^{\frac{1}{2}}}{(\log \log N_E)^{\frac{3}{2}}},$$

is contained in the interval  $[0.86, 1.5]$  for all conductors  $25 \leq N_E \leq 10^{250}$ , and hence it is impossible to decide which of (17) or (18) is more likely to be true with the current data. Let us compare these conjectures with the elliptic curves appearing in [EW]:

$r_{\text{al}}(E)$	$N_E$	$\log N_E / \log \log N_E$	$\sqrt{\log N_E \log \log N_E}$
5	$1.9 \cdot 10^7$	6.874	5.946
6	$5.2 \cdot 10^9$	8.338	7.198
7	$3.8 \cdot 10^{11}$	9.358	8.122
8	$2.5 \cdot 10^{14}$	10.773	9.469
9	$3.2 \cdot 10^{16}$	11.759	10.448
10	$1.0 \cdot 10^{18}$	12.861	11.582
11	$1.8 \cdot 10^{22}$	14.203	13.018

and those appearing in [Me]<sup>3</sup>:

$r_{\text{al}}(E)$	$N_E$	$\log N_E / \log \log N_E$	$\sqrt{\log N_E \log \log N_E}$
3	$5.1 \cdot 10^3$	4.277	3.980
4	$5.4 \cdot 10^5$	5.839	5.118
5	$1.7 \cdot 10^8$	7.482	6.455
6	$5.1 \cdot 10^{10}$	8.893	7.696
7	$3.2 \cdot 10^{12}$	9.841	8.574
8	$1.8 \cdot 10^{15}$	11.181	9.870
9	$7.0 \cdot 10^{19}$	13.215	11.956
10	$5.2 \cdot 10^{22}$	14.386	13.217
11	$1.8 \cdot 10^{24}$	14.989	13.884
12	$2.7 \cdot 10^{29}$	16.903	16.073
13	$2.1 \cdot 10^{38}$	19.885	19.699
14	$3.6 \cdot 10^{37}$	19.640	19.391

Both of these tables show that (17) and (18) are equally likely to be true.

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<sup>3</sup>The first column of this table is actually a lower bound on the rank, which can be shown to equal the rank under standard hypotheses.

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